Sound localization with communications headsets: Comparison of passive and active systems

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ABSTRACT

Studies have demonstrated that conventional hearing protectors interfere with sound localization. This research examines possible benefits from advanced communications devices. Horizontal plane sound localization was compared in normal-hearing males with the ears unoccluded and fitted with Peltor H10A passive attenuation earmuffs, Racal Slimgard II communications muffs in active noise reduction (ANR) and talk-through-circuitry (TTC) modes and Nacre QUIETPRO™ communications earplugs in off (passive attenuation) and push-to-talk (PTT) modes. Localization was assessed using an array of eight loudspeakers, two in each spatial quadrant. The stimulus was 75 dB SPL, 300-ms broadband noise. One block of 120 forced-choice loudspeaker identification trials was presented in each condition. Subjects responded using a laptop response box with a set of eight microswitches in the same configuration as the speaker array. A repeated measures ANOVA was applied to the dataset. The results reveal that the overall percent correct response was highest in the unoccluded condition (94%). A significant reduction of 24% was observed for the communications devices in TTC and PTT modes and a reduction of 49% for the passive muff and plug and muff with ANR. Disruption in performance was due to an increase in front-back reversal errors for mirror image spatial positions. The results support the conclusion that communications devices with advanced technologies are less detrimental to directional hearing than conventional, passive, limited amplification and ANR devices.

Keywords: Auditory perception, directional hearing, hearing protection

The present study examined the effects of two advanced communications systems on sound localization. These were developed to enhance speech understanding in noise among members of military sections. However, to date, the effects of such devices on other auditory functions such as sound detection and discrimination, speech understanding and sound localization, have not been well documented. With respect to sound localization, previous studies have demonstrated that, in general, performance will be compromised by the use of conventional, passive hearing protective earplugs and earmuffs.[1,2] Muffs are particularly disruptive because they interfere with spectral cues provided by the outer ears (pinnae) in aid of front/back discrimination. While right/left discrimination is reasonably accurate with single devices, the use of muffs and plugs in combination, a common solution for reducing low-frequency noise exposure, produces severe disruptions.[3] Practice may provide the opportunity to optimize the use of other cues such as loudness differences but total adaptation does not occur.[4] Although free head movement may restore horizontal plane performance, subjects still take longer to make the judgment with the devices fitted.[5,6]

In recent years, attention has shifted to the exploration of possible benefits for sound localization that may accrue from nonlinear earmuffs.[7] These devices incorporate either limited amplification or active noise reduction (ANR) accomplished using microphones housed in one or both ear cups.[8] In the case of limited amplification, low-level signals may be amplified by up to 10 dB until a preset risk criterion is reached (e.g., 82 dBA). Beyond the criterion, sound attenuation will increase by 1 dB for every 1 dB increment in sound level until the passive attenuation of the muff (e.g., 35 dB) is reached. In the case of ANR, an electronic circuit housed within the muff inverts the incoming waveform and adds it out of phase to the original. Components of the two waveforms which are out of phase will cancel, thereby reducing the overall level. ANR is limited to frequencies below 1 kHz that often characterize industrial or military environments (e.g., aircraft cockpit).

Noble et al.[9] compared subjects' ability to localize sound sources in a 20-speaker array comprising both horizontal, −90 to +90 deg and vertical, −72 to +90 deg elements, arranged as two intersecting arcs at their midpoints and positioned frontally or laterally in relation to the subject's head. A comparison was made of localization of short bursts of 85-dBA random noise with the ears unoccluded and fitted with conventional earplugs and earmuffs, two types of diotic limited amplification earmuffs (single microphone) and two types of dichotic limited amplification earmuffs (microphone in each ear cup). Subjects gave 80% correct responses when

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their ears were unoccluded. Diotic devices severely disrupted performance (8% correct). Decrements observed for the conventional and dichotic devices relative to unoccluded listening were similar and close to 50% and 57% for the frontal and lateral arrays, respectively. Abel and Hay[10] evaluated interference with interaural time-of-arrival difference (ITD) and interaural level difference (ILD) cues with conventional plugs and muffs and with muffs incorporating dichotic limited amplification. Subjects localized narrowband sounds centred at 0.5 and 4 kHz emitted by a horizontal array of six speakers positioned 60 deg apart. Right/left judgments based on the ILD cue were affected by all three devices but more so by the electronic device. Front/back judgments were affected more by the muffs than the plugs but the conventional and electronic muffs were essentially the same. There was no evidence of interference with the ITD cue. Abel and Paik[11] found that earmuffs with ANR were as disruptive as those providing conventional passive attenuation.

In the present study, horizontal plane sound localization was examined in normal-hearing individuals fitted with two advanced communications systems, in comparison with conventional earmuffs and plugs, ANR muffs and unoccluded listening. Both devices are now commonly used in military operations. However, to date, no information has been published on their effect on directional hearing ability. In particular, the study was designed to determine whether there might be an enhancement in performance in the talk-through modes of operation relative to that obtained with either conventional attenuation or ANR. In this first-in-a-series of planned studies, the comparisons among devices were made in quiet to allow an assessment of the effect of the communications technology on sound localization with the ears occluded. The data also provided a baseline for later evaluation of the same devices in military operational noise.

Methods

Experimental design

The study protocol was approved in advance by the Research Ethics Committee of our Institute. Twelve normal-hearing male subjects aged 18-55 years participated in a two-hour test session. None had previously participated in a sound localization study. All had some experience in wearing hearing protection. Subjects provided written informed consent before participating. Sound localization ability was assessed using a horizontal array of eight loudspeakers surrounding the subject at a distance of 1 m from the centre head position at ear height. Two speakers were positioned in each of the four spatial quadrants, 15 deg from the midline and interaural axes of the head, respectively, at the following azimuth angles: 15, 75, 105, 165, 195 (−165), 255 (−105), 285 (−75) and 345 (−15) degrees [Figure 1]. This placement enabled determination of right *vs* left and front *vs* back mirror image reversal errors for azimuths close to each axis. The
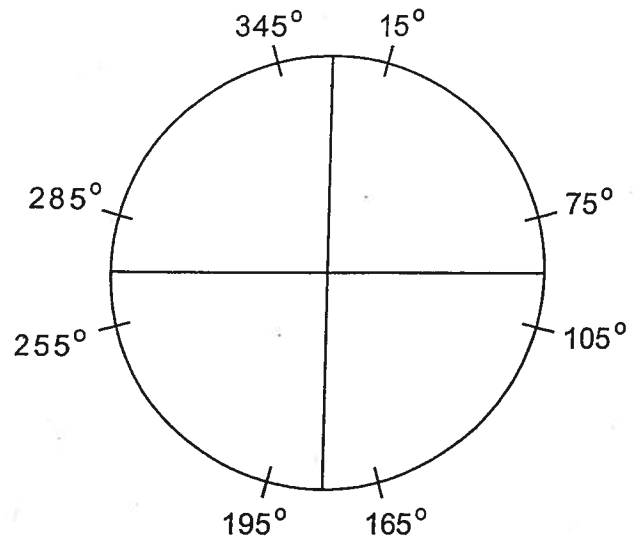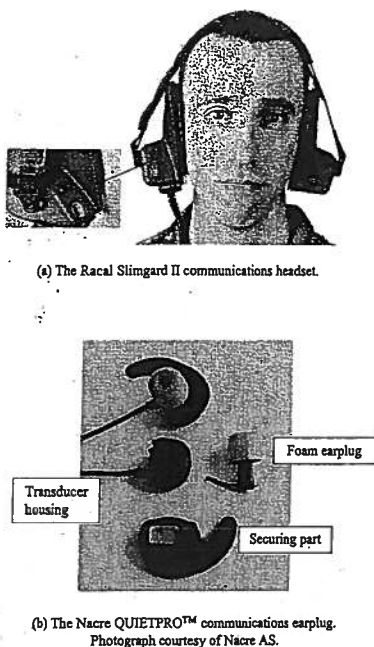

Figure 1: The 8-speaker array

stimulus was a 75 dB SPL, 300-ms broadband white noise with a 50-ms rise/decay time to minimize onset transients. Broadband noise allows the observer access to binaural (ITD and ILD) and spectral cues in combination.[12]

There were six listening conditions. In each subject, sound localization was assessed with the ears unoccluded (Unoccl) and fitted with Peltor H10A passive earmuffs (Aearo Co, Indianapolis, IN), Racal Slimgard II active earmuffs (Racal Acoustics Ltd, Harrow, UK) in active noise reduction (ANR) and talk-through circuitry (TTC) modes of operation and Nacre QUIETPRO™ communications earplugs (Nacre, Trondheim, Norway) in passive attenuation (OFF) and active push-to-talk (PTT) modes. For the protected conditions, participants were given verbal instructions for fitting the devices before doing so themselves. Fits were then checked by a trained technician to ensure that the devices were well-seated. This is a variation of Method A (Experimenter-Supervised Fit) described in ANSI Standard S12.6-1997.[13]

Based on the manufacturers' information sheets and specifications, the Peltor earmuff is a conventional passive level-independent hearing protective device with sound attenuation values ranging from 21-41 dB from 0.125 to 8 kHz. The Racal earmuff provides 22-37 dB of total (passive plus active) attenuation from 0.125-8 kHz with ANR operational. Noise stimuli detected by a small sensor microphone in the ear shell are inverted in phase and driven back into the ear by an earphone, resulting in an increase in the attenuation normally achieved below 1 kHz. In the TTC mode, the headset reproduces external sounds at the two ears using a pair of externally mounted microphones [Figure 2a]. Sound level is limited to 85 dBA. The Nacre QUIETPRO™ device comprises two ear pieces (transducer housing, securing part and disposable foam earplug) and a

(a) The Racal Slimgard II communications headset.

(b) The Nacre QUIETPRO™ communications earplug.
Photograph courtesy of Nacre AS.

Figure 2: Photographs of the Racal and Nacre communications systems

pocket-sized control unit [Figure 2b]. The transducer houses two miniature microphones within and outside the ear canal and one loudspeaker. In the OFF mode, the earplug provides 25-40 dB of passive attenuation from 0.125-8 kHz. With PTT continuously on, ANR is automatically activated and the total attenuation (passive plus active) is 35-40 dB from 0.125 to 8 kHz. Subjects were instructed not to adjust the volume which was set at the unit's default (*i.e.*, unity gain). This proved to be a comfortable listening level. As with the Racal headset, sound level was limited to 85 dBA.

Subjects

Subjects were recruited with the aid of an email sent to all employees of our Institute. Volunteers were screened for a history of ear problems and hearing loss (HL), the use for medications that might affect concentration and the need for eyeglasses to view objects at close range. Studies have shown that fitting an earmuff over the temple bar of glasses may result in a poor seal between the device and the external ear compromising sound attenuation.[14] All subjects were fluent in English to ensure that the instructions would be understood. Individuals who met these criteria underwent a hearing screening test. Those with normal hearing, *i.e.*, pure-tone hearing thresholds no greater than 20 dB HL at 0.5, 1, 2 and 4 kHz in each ear and interaural differences in threshold no greater than 15 dB at these frequencies were eligible for this study.[15] The latter constraint ensured that subjects would not have a bias in directional hearing. For those who passed the hearing test, the experimenters confirmed that the Nacre QUIETPRO™ earplug system passed an automatic acoustical earplug-seal test with one of the three available sizes.

Apparatus

Subjects were tested individually while seated in the center of a double-walled, semireverberant soundproof booth (Series 1200; IAC, Bronx, NY) with inner dimensions of 3.5 m (L) × 2.7 m (W) × 2.3 (H) m. Reverberation times were 0.6 s at 0.125 kHz and 0.25 kHz, 0.4 s from 0.5 kHz to 4 kHz and 0.3 s at 6 kHz and 8 kHz.[16] Ambient noise was less than the maximum allowed for audiometric testing.[17]

The instrumentation and calibration methods have been described previously.[16] The broadband noise stimulus was generated by a noise generator (Type 1405; Brüel &Kjaer Instruments, Norcross, GA). The stimulus parameters, trial by trial loudspeaker selection, timing of events and logging of responses were controlled by a Coulbourn Instruments modular system (Lehigh Valley, PA). Stimulus envelope shape and duration were fixed using a selectable envelope shaped rise/fall gate (Coulbourn S84-04). Level was specified using a programmable attenuator (Coulbourn S85-08) and a set of integrated stereo amplifiers (Realistic SA-150; Radio Shack Corp, Fort Worth, Tx). The stimuli were presented by a set of eight loudspeakers (Minimus 3.5; Radio Shack Corp, Fort Worth, Tx) closely balanced with respect to output levels (1.5 dB) and frequency response from 0.125-12 kHz (2.5 dB). Subjects signified their spatial judgments by means of a specially designed laptop response box with a set of eight microswitch buttons in the same configuration as the speaker array, both in number of elements and azimuth angles. The audio system was accessed by a personal computer via IEEE-488 (Institute of Electrical and Electronics Engineers, Inc, New York, NY) and Lablinc interfaces (Coulbourn Instruments, Lehigh Valley, PA) and digital I/O lines.

Procedure

The order of presentation of the six ear conditions was counterbalanced across the twelve subjects. For each condition, subjects were presented one block of 120 forced-choice loudspeaker identification trials. A block comprised 15 presentations from each of the eight speakers in randomized sets of eight. Each trial began with a ½-sec warning light on the response box followed by a ½-sec delay and the presentation of the 300-ms broadband noise stimulus. When the warning light flashed, the subject focused on a straight-ahead visual target affixed to the wall of the booth. This ensured that the speaker array and coordinate system of the head were aligned. Subjects were instructed to sit squarely and to try to minimize head movement although the head was not restrained. Previous research has shown that head movements may help to resolve front/back confusions.[6]

The rate of presentation of stimuli was approximately one every seven seconds. Following each presentation, the subject looked down at the response box and depressed the button corresponding to the perceived location of the stimulus. Guessing was encouraged. No feedback was

given about correctness of the judgment. Subjects were advised to use both hands for responding, the right hand for buttons on the right and the left hand for buttons on the left to eliminate the possibility of errors from crossing the hand to the contralateral side. At the start of the session, subjects were given a set of sixteen practice trials, two per speaker in randomized sets of eight with feedback and with the ears unoccluded. This enabled the experimenter to confirm that the instructions had been understood and allowed the subject the opportunity to map the loudspeaker array onto the array of response buttons.

Results

Overall percent correct [P(C)] in sound localization was highest for unoccluded listening (94.1%) followed by the Nacre plug with PTT (71.1%), the Racal muff with TTC (69.2%), the Nacre plug in the OFF (passive) mode (51.7%), the Peltor passive muff (46.1%) and the Racal muff with ANR (36.1%). A repeated measures ANOVA[18] applied to these data indicated that ear condition was significant (p<0.0001). Post hoc pairwise comparisons using Fisher's LSD showed that unoccluded listening resulted in significantly better performance than all other conditions (p<0.001). The Nacre plug with PTT and Racal muff with TTC were no different and significantly better than the passive muff and plug and ANR muff (p<0.001). In order to determine whether subjects benefited from practice over the course of the trial block, the P(C) for the first and last set of 16 trials were compared. An improvement of 5% was observed in the unoccluded condition. Across the five occluded conditions, improvements ranged from −1% (Racal muff with ANR) to 8.1% (Nacre plug with PTT). A repeated measures ANOVA showed a significant overall main effect of practice of 3.5% (p<0.05).

Subjects had no difficulty in determining that the target sound had emanated from the right or left hemisphere (90% or better) except when wearing the Racal muff with ANR (81.5% for the left hemisphere). Discrimination of front from rearward speakers proved to be more problematic. Figure 3 shows the mean P(C) associated with sounds coming from the four speakers in front of and behind the interaural axis of the head, respectively. A score of 50% signifies chance performance. In the unoccluded condition, subjects scored 95.3 and 93.6% for speakers in the front and back, respectively. The protected conditions were similar to each other for the speakers in the back ranging from 58.7% (Racal muff with ANR) to 70.1% (Racal muff with TTC). A wider spread in mean P(C) across ear conditions was evident for the speakers in the front. The lower the score, the more likely that sounds from the front were localized to the rearward hemisphere. The Nacre plug with PTT and Racal muff with TTC fared best in this regard (75.9% on average); the Peltor passive muff, Nacre plug in passive mode and Racal muff with ANR fared worst (43.8% on average). Standard deviations associated with the means for speakers in the front and back were all close to 30% compared with 9% for unoccluded listening, denoting relatively wide individual differences.

The ability to discriminate among the four spatial quadrants is depicted in Figure 4. The mean P(C) associated with correctly determining that sounds had been emitted by the two speakers in each of the Right-Front (RF), Right-Back (RB), Left-Back (LB) and Left-Front (LF) spatial quadrants is presented for each of the six listening conditions. For this analysis, judgments were counted correct as long as the spatial quadrant was correctly identified, regardless of whether the speaker in that quadrant (choice of two) was also correctly selected. In the unoccluded condition, the P(C)s for the four
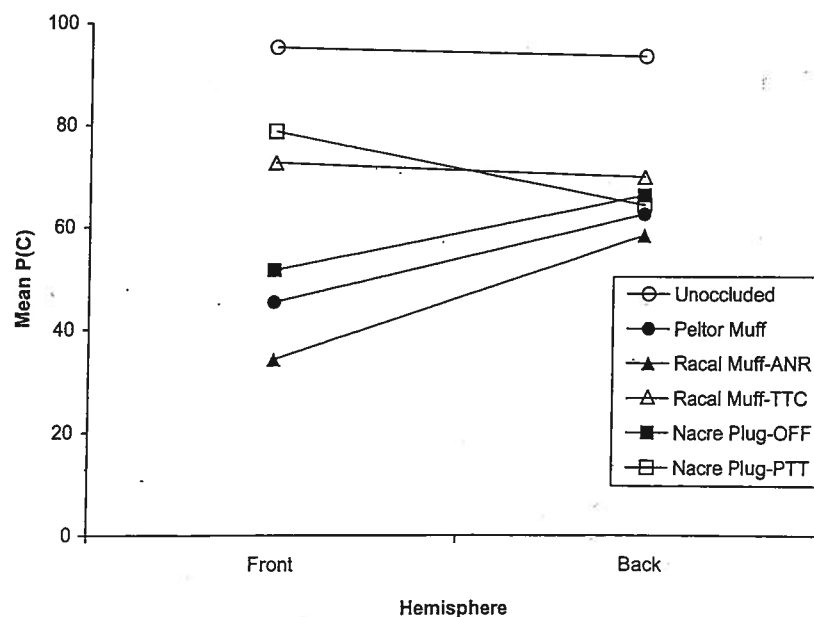

Figure 3: Accuracy in discriminating between front and rearward speakers for each of the six ear conditions
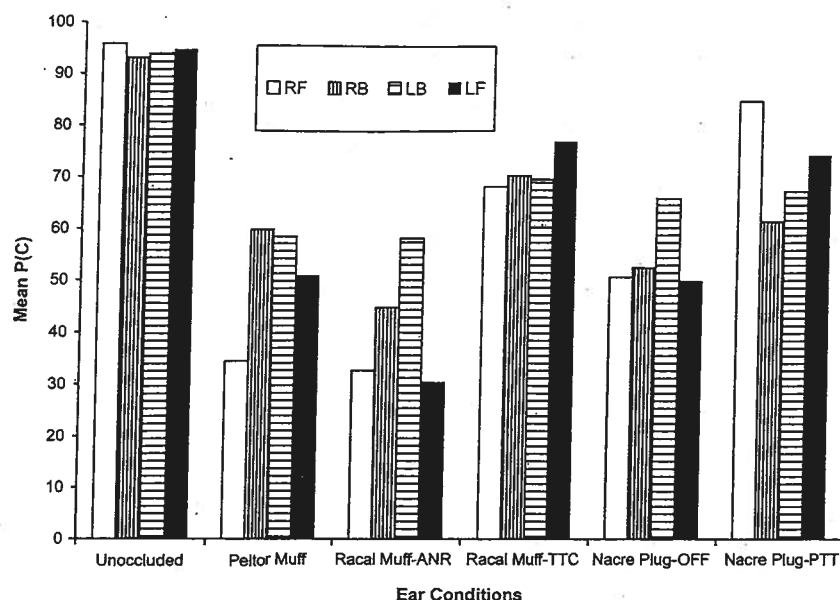
Figure 4: Quadrant discrimination for the six ear conditions. The percentage of correct trials is shown for each of the Right-Front (RF), Right-Back (RB), Left-Front (LF) and Left-Back (LB) quadrants

Table 1: Azimuthal accuracy in horizontal plane sound localization for each of the six ear conditions ($n = 12$)

Azimuth (deg)	Ear condition					
	Unoccl	Peltor muff	Racal		Nacre	
			ANR	TTC	OFF	PTT
15	95.6 (15.4)*	21.7 (32.3)	13.9 (20.4)	75.6 (39.9)	32.2 (35.9)	75.6 (36.9)
75	95.0 (9.5)	40.6 (26.7)	39.4 (30.8)	60.0 (31.0)	55.6 (39.7)	88.3 (18.2)
105	86.1 (22.1)	56.1 (39.5)	43.3 (25.8)	59.5 (33.2)	41.1 (32.9)	41.1 (32.0)
165	98.9 (2.6)	47.2 (36.6)	36.7 (32.6)	72.2 (33.5)	58.9 (40.6)	81.1 (31.4)
−15	92.8 (25.0)	35.0 (37.0)	19.4 (33.2)	76.7 (40.6)	45.0 (47.1)	72.8 (38.6)
−75	96.7 (6.0)	62.8 (34.2)	41.1 (39.3)	77.2 (32.8)	49.4 (39.2)	75.6 (34.6)
−105	87.8 (12.3)	50.6 (35.4)	47.8 (34.8)	51.1 (35.8)	62.2 (40.6)	57.8 (33.9)
−165	100.0 (0.0)	54.4 (28.1)	46.7 (36.3)	81.7 (29.6)	68.9 (31.2)	76.7 (35.6)

*Mean P(C) (SD)

quadrants were consistently high, ranging from 93.1-95.8%. Across the devices tested, the P(C)s for the four quadrants were only similar (differences no greater than 10%) in the case of Racal muff with TTC (68.1-77.0%). Ranges of values observed for the other ear conditions were 61.4-84.7% for the Nacre plug with PTT, 50.0-65.8% for the Nacre plug in the passive mode, 34.4-60.0% for the Peltor passive muff and 30.3-58.1% for the Racal muff with ANR. All the mean P(C)s were above chance (25%) although the relatively high standard deviations (25.8-40.6%) for the protected conditions compared with those for the unoccluded condition (6.2-12.3%) indicated wide differences in quadrant discrimination across subjects. Due to the differences in the standard deviations between the unoccluded and protected conditions, a repeated measures ANOVA was applied only to the protected data. There were significant effects of ear condition (p<0.0001) and ear condition by spatial quadrant (p<0.0001). Post hoc pairwise comparisons (p<0.05 or better) using Fisher's LSD test confirmed that there were no differences due to quadrant for the Racal muff with TTC. The Nacre plug with PTT

showed a front advantage, the Nacre plug in the passive mode and Racal muff with ANR showed a back advantage and the Peltor passive muff a right-front disadvantage.

Azimuthal accuracy was similar for corresponding azimuths (mirror image positions) on the left and right sides of space [Table 1]. To facilitate comparisons, azimuth angles on the left side have been expressed as negative numbers relative to the 0 deg straight ahead position. There were only seven instances out of the 24 tabulated where the difference in outcome for mirror image azimuths on the left and right was greater than 10% (*e.g.*, Nacre with PTT, ± 105 deg). As shown in Table 2, incorrect responses were due in large part to front-back mirror image reversal errors regardless of the ear condition. The prevalence of these was calculated by dividing the number of mirror image reversal errors by the total number of errors for the azimuth. To assess right-left mirror image reversal errors, the results were averaged across front and back spatial hemispheres. Thus, for example, the entry for 345/15 (a response of 345 deg given a stimulus of 15 deg)

Table 2: Mean percentage of mirror image reversal errors (SD), averaged across front and back hemispheres for right-left errors and across right and left hemispheres for front-back errors (n = 12)

Error type	Reversal	Unoccl	Peltor muff	Racal muff		Nacre plug	
				ANR	TTC	OFF	PTT
R-L[1]	345/15*	0.2 (1.0)	4.2 (8.5)	8.1 (11.8)	0.0 (0.0)	7.0 (12.9)	0.0 (0.0)
	15/345	0.0 (0.0)	7.2 (7.8)	8.1 (12.5)	1.1 (3.0)	10.0 (10.0)	1.1 (2.2)
	285/75	0.0 (0.0)	0.3 (1.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
	75/285	0.0 (0.0)	0.0 (0.0)	1.7 (4.8)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
F-B[1]	165/15	5.6 (19.3)	45.3 (30.5)	41.1 (33.0)	21.7 (36.5)	38.1 (35.4)	21.4 (35.1)
	15/165	0.0 (0.0)	21.9 (31.3)	36.1 (35.6)	14.7 (30.4)	18.1 (32.7)	18.6 (27.1)
	105/75	3.9 (6.0)	44.5 (30.0)	48.6 (24.2)	30.8 (26.2)	40.0 (32.7)	18.1 (24.4)
	75/105	12.5 (15.7)	43.3 (31.7)	36.1 (27.3)	44.4 (32.4)	43.6 (29.7)	50.6 (29.7)

[1] R-L: Confusion of speakers located on the right and left sides of the subject; F-B: Confusion of speakers located in front of and behind the subject.

*345|15: The perception that the speaker located at 345 deg had emitted the stimulus given that it had actually been presented from the speaker located at 15 deg.

is the average of 345/15 deg and 195/165 deg [Figure 1]. To assess front-back mirror image reversal errors, the results were averaged across right and left spatial hemispheres.

The data indicate that the prevalence of right-left mirror image reversal errors was close to 0%. Exceptions were confusion of azimuths on either side of the midline axis (15 and 345 deg) when wearing the Peltor passive muff, the Racal muff with ANR and the Nacre plug in passive mode. In these conditions, the percentage of mirror image reversal errors ranged from 4-10%. Front-back mirror image reversal errors were far more likely, particularly in the protected conditions, ranging from 15-51%. For speakers close to the midline axis, back/ front errors (165/15) were relatively more prevalent than front/back (15/165). For speakers close to the interaural axis the prevalence of back/front (105/75) and front/back (75/105) errors was similar (about 41%) for all but the Nacre plug with PTT. For this device, the prevalence of front/back mirror image reversal errors was 51%, compared with 18% for back/front.

Discussion

This study was conducted to determine the possible benefits that might accrue for sound localization from two advanced communications devices, a muff with TTC operational and a plug with PTT operational, compared with unoccluded listening and listening with conventional passive hearing protective earmuffs, passive earplugs and a muff incorporating ANR. As expected, performance was best with the ears unoccluded. The passive muff, the passive plug and muff with ANR were the most disruptive and quite similar in outcome. The latter finding is in line with previous reports.[9-11] The average overall P(C) for these three devices for discrimination of the eight speakers was 45% compared with 94% for unoccluded listening, exceeding chance performance (12.5%) by 32%. The disruption in performance was mainly related to problems discriminating between front and rearward speakers. Subjects tended to hear sounds in front as coming from behind. Differences between mean front and rearward quadrant P(C)s were 20% with ANR, 16% for the passive muff and 9% for the passive plug. The smaller front-back difference observed for the plug compared

with the muffs is in line with earlier findings.[10] The prevalence of back/front mirror image reversal errors averaged across the three devices and speakers located close to the midline and interaural axes was 43%, indicating that almost half the presentations were incorrectly labelled, compared with 33% for front/back mirror image reversal errors.

Protected performance was significantly better with the two communications headsets when the TTC and PTT modes, respectively, were operational. Overall, subjects scored 70% correct responses. Comparative improvements relative to the passive muff and plug and muff with ANR were reminiscent of benefits observed with dichotic (two microphones) vs diotic (one microphone) earmuffs.[9] With these two communications options, P(C)s for the front and back hemispheres were nearly the same at 71% in contrast to the wide difference observed for the other three devices. With the Racal communications muff in TTC mode mirror image reversal errors were more prevalent (38%) for the positions on either side of the interaural axis, 75 and 105 deg, than for the positions close to the midline, 15 and 165 deg (18%). The likelihood of front/back and back/front errors was similar. With the Nacre communications plug in PTT mode, again, mirror image reversal errors were more prevalent close to the interaural axis. However, subjects reported 51% of presentations from 105 deg as coming from 75 deg but only 18% of presentations from 75 deg as coming from 105 deg. Further analysis revealed that the relatively high percentage of front/back errors for the interaural position occurred on both the right and left sides but was more prevalent on the right (59 vs 42%). This finding may be unique to the particular device used for the study and requires further study.

The practical implications of the findings are that advanced communications technologies provide a way to facilitate information exchange among members of military sections while at the same time reducing high-level noise exposure without severely disrupting the ability to localize auditory warnings. Bias in perceiving that sounds had been emitted by speakers in back was less evident with these devices than with conventional hearing protectors. The reason for

the comparative benefit for sound localization realized from the advanced communications systems is unclear. In all six listening conditions, the level of the stimulus at the eardrum was sufficient for accurate horizontal plane sound localization.[19] However, it may be that the microphones incorporated in these devices increased the difference in the perceived loudness of front and rearward sound sources. This would account for the higher prevalence of front-back mirror image reversal errors for sources closely positioned on either side of the interaural axis compared with those near the midline axis. This laboratory study represents the first stage of assessing the relative benefit of advanced communications headsets for sound localization. Field testing in noise is essential to determine the utility in operational settings.

Conclusions

The results suggest that in situations where personal hearing protectors must be worn to limit exposure to high-level noise, advanced communications headset technologies will be less detrimental to directional hearing ability than conventional passive muffs and plugs and ANR muffs. The latter result in significant decrements in the ability to discriminate between front and rearward sound sources and thus may constitute a hazard. Although an overall reduction in performance of 24% relative to unoccluded listening was evident for the two communications devices tested, subjects were equally able to identify front and rearward sound sources and spatial quadrants. Front-back mirror image reversal errors mainly occurred for sound sources located on either side of the interaural axis of the head. These were positioned 30 degrees apart, an angular separation that may be less than the resolution required in the field.

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Glossary

ANR - active noise reduction; technology incorporated in hearing protectors for low-frequency sound reduction
ITD - interaural time-of-arrival difference; cue for sound localization
ILD - interaural level difference; cue for sound localization
PTT - push-to-talk; mode of operation for communications device
TTC - talk-through-circuitry; mode of operation for communications device
Dichotic - signal presented to each ear differently (*e.g.* by different microphones)
Diotic - signal presented to each ear identically (*e.g.* by the same microphone)